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FC
VTOL TRANSPORT AIRCRAFT

...ive Study

EFFECT OF PERFORMANCE CRITERIA ON THE OPTIMUM DESIGN OF THE TILT-WING PROPELLER AND VERTODYNE
VERTOL REPORT NO. R-84

VERTOL Aircraft Corporation

formerly - Piasecki Helicopter Corporation

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Comparative Study of Various Types of

VTOL Transport Aircraft

EFFECT OF PERFORMANCE CRITERIA ON THE OPTIMUM DESIGN OF THE TILT-WING PROPELLER AND VERTODYNE REPORT R-84

Vertol Aircraft Corporation Morton, Pennsylvania

ONR ARMY

A Combined

Research and Development Program

Contract NONR 1681(00)

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JULY 13, 1956

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I. SUMMARY

In order to more thoroughly investigate the effects of various performance criteria on the optimum design of VTOL aircraft, a parametric study suitable for solution on IBM computers was made for the more promising VTOL configurations. The results of the broad comparative study, reported in Reference 1, indicated that for the mission requirements, the Tilt Wing Propeller concept is the optimum VTOL aircraft for cruising speeds of 250 to 350 miles per hour while for higher cruising speeds (400 to 500 mph) the Vertodyne appears to be the more suitable aircraft. Consequently, these two configurations have been chosen for inclusion in this report in order to determine the effect of hovering altitude, hovering time and cruise altitude on the minimum gross weight of each aircraft.

Each aircraft is designed for a radius of action of 425 statute miles carrying an outbound payload of 8000 pounds and an inbound payload of 4000 pounds. Power plant performance and weight trends used throughout this study reflect the anticipated state of art for the year 1962. Much of this data is the same as that previously shown in Reference 1.

In order to evaluate the effect of a given performance criterion, it is obviously necessary to keep constant the remaining variable. On this basis, hovering ceiling has the greatest percentage effect on design gross weight; cruise altitude has a somewhat lesser effect. Hovering duration, at least for the times considered (from 1 to 10 minutes), has the least effect on design gross weight. However, it is the combined effect of the various performance variable that is important in a final evaluation. These results are best summarized graphically and are presented in Figures 1 through 4.

II. INTRODUCTION

A. General Method of Parametric Analysis

The basic approach to the parametric program for each of the configurations mentioned in the Summary can be most easily discussed by referring to the simplified flow type diagram shown below:

INPUT DATA

$$HP_{inst_1} = f \text{ (hovering power)} \qquad HP_{inst_2} = f \text{ (cruise power)}$$

Larger HP_{inst}

$$W_{basic} = f\,(HP_{inst_1}, \text{ Input Data})$$

$$R_{outbound} = V \int_{W_1}^{W_{TO}} \frac{dW}{\text{Fuel Flow}} \qquad R_{inbound} = V \int_{W_{BASIC}}^{W_2} \frac{}{\text{Fuel Flow}}$$

Where $W_1 = f\,(W_2, \text{ Hovering Time})$

$R_{outbound}$ and $R_{inbound}$ are balanced

From this diagram it can be easily seen that the procedure is to evaluate the power requirements in hovering and in cruise for the particular set of input data. This input data reflects basic aerodynamic variables as well as the performance and payload requirements of a given mission. The larger of these two power requirements dictates an installed power upon which the basic weight of the aircraft depends. Having thus established the basic weight by converting the weight components into the aerodynamic input data being investigated, it is possible to proceed to the cruise and hovering requirements of the mission. Assuming a weight at the radius mission midpoint, the distance outbound and inbound can be evaluated with consideration given to any time in hovering at the scene. The balancing of these radii, of course, is a solution to the given set of input data and the process can be repeated for a new set of aerodynamic or mission variables.

Each of the specific programs follows this general procedure with appropriate variations to account for the differences between individual concepts. A detailed chart showing the various equations to be solved in a set up of this form has been

presented in each configuration section immediately after the introduction describing the particular aircraft type. Included also with this chart is a summary table indicating the relationship between the IBM input constants and the aerodynamic weight and power plant symbols. The basic aerodynamic variables for which each configuration has been programmed are shown at the top of each detailed chart. However, in order to minimize the number of aerodynamic input variables the Tilt Wing Propeller was investigated for a speed of 300 mph and the Vertodyne for 450 mph. It should be realized that for each configuration these speeds are not optimum for every cruise altitude considered. However, they are representative for each configuration.

B. Tilt Wing Propeller Analysis

This configuration employs a tilt wing propeller combination with interconnecting shafts. The wing has been assumed completely immersed in the propeller slipstream so that the span can be expressed as a function of disc loading and gross weight. The wing planform area has been dictated through wing loading as a prime variable so that the aspect ratio of the wing then is included indirectly in the analysis as a function of propeller diameter and wing loading. The tail surface area has been introduced into the equations as a percentage of total wing area.

The hovering power requirements are calculated through an aerodynamic efficiency applied to the ideal rotor power (Reference 1). Power required in forward flight is determined by a flat plate drag area composed of an imput constant for fuselage with wing and tail surface area varying, of course, with wing loading. The change in the total parasite drag of the ship with wing lift coefficient is reflected through the usual airplane efficiency factor applied to the wing induced power term.

The body weight has been based on wetted area which has been introduced as a function of gross weight, wing loading and disc loading. The drive system has for purposes of simplicity been based on the assumption of a four propeller configuration.

The number of installed engines has been based at least for the initial purposes of this study on the sea level military rating of the Allison 550B-1 turboprop. Power plant characteristics likewise reflect an average of turboprop engines of this type for the year 1962, as shown in Section E.

Because of the high power requirements of VTOL aircraft and hence a greater number of installed engines, provisions have been incorporated in this and subsequent programs to evaluate the effect of cruising on all or part of the installed engines.

TABLE 1 - DETAIL FLOW DIAGRAM

Input Variables	$W_{T.O.}$	
	ω_s	
	ω	
	V	

$$HP_{INST._1} = K_1\left(SHP_{REQ.\,HOV.}\right) = \frac{.00128\, K_1 W_{T.O.}\sqrt{\frac{\omega}{K_2}}}{K_5\left(K_3 + K_4\,\omega^{.23}\right)}$$

$$HP_{INST._2} = K_{23}\left(SHP_{REQ.\,CRUISE}\right) = \frac{K_{23} V}{375 K_{23} K_5}\left[Ⓐ + Ⓑ\right]$$

Use Larger Value $\longrightarrow n_{INST.} = \frac{HP_{INST.}}{5200}$ where, $n_{INST.} \geqq 2 \leqq 8$ (Use Next Larger Integer!)

$$W_{BASIC} = 28.2 K_6\left[\frac{HP_{INST.} W_{T.O.}^2}{K_1 K_6^2 K_7^2 \omega^{1.5} K_5^{.5}}\right]^{.31} + K_3\left[\frac{W_{T.O.}}{\omega_s^{.?}} + K_4\omega_s\left(.862\sqrt{\frac{K_6 W_{T.O.}}{\omega}} + K_{10} + K_{11}\right)^3\right] + K_{12} W_{T.O.} + .195\left\{W_{T.O.}^2\left[K_{13} + \frac{K_{33} W_{T.O.}}{\omega_s\left(.862\sqrt{\frac{K_6 W_{T.O.}}{\omega}} + K_{10} + K_{11}\right)}\right]\right\}^{.34} + K_{14}\left(HP_{INST.}\right) + 1.63\left[\frac{HP_{INST.}\, n_{INST.}}{K_1}\right]^{.5} +$$

$$37.0\left(\frac{HP_{INST.}}{K_7 K_1}\right)^{.5}\cdot\left(\frac{K_6 W_{T.O.}}{\omega}\right)^{.25} + .098\left(\frac{HP_{INST.}}{K_6 K_1}\right)^{.5}\cdot\left[.862\sqrt{\frac{W_{T.O.}}{K_6\,\omega}}\left(K_6 - 1\right) + K_{10} + K_{11}\right] + .92\left[\frac{HP_{INST.} W_{T.O.}}{K_1 K_7 K_6\,\omega}\right]^{.5}\cdot\left[\frac{W_{T.O.} K_6}{\omega}\right]^{.25} + K_{15} + K_{16} + K_{17} + \left(n_{INST.}\right)\left[.96\left(\frac{HP_{INST.}}{n_{INST.}}\right)^{.67} + .203\left(\frac{HP_{INST.}}{K_1 K_6}\right)^{.5} + K_{25}\right]$$

Assume A W_1 & Evaluate $R_{OUTBOUND}$:

$$R_{OUTBOUND} = \int_{W_1}^{W_{T.O.} - .0167 K_{20} K_{19} K_{21} K_{34} HP_{INST.}} \frac{\left(375 K_{22} K_5\right) dW}{K_{19} K_{21}\left[Ⓐ + Ⓒ\right]\left[.393 + 20690 K_{24}^2\right]\left\{.512\left[\left[\frac{V K_{31}\left[Ⓐ + Ⓒ\right]}{K_{22}(375) K_{23} K_5 \left(HP_{INST.}\right)} - 1.474 - .0329\left(\frac{V}{100}\right)\right]\right]^2 + .335 - .0163\left(\frac{V}{100}\right)^{1.66}\right\}}$$

$$\left\{\begin{array}{l} n_{CR.} = 1.25\left(n_{INST.}\right)\dfrac{V K_{31}\left[Ⓐ + Ⓒ\right]}{375 K_{23} K_5 HP_{INST.}} \\ \text{where, } n_{CR.} \geqq 2 = 8 \text{ (Use Next Larger Integer)} \\ \therefore K_{22} = \dfrac{n_{CR.}}{n_{INST.}} \end{array}\right.$$

$$W_2 = W_1 + K_{17} - K_{29} - \left[\frac{K_{19} K_{20} K_{21} K_{34}}{33000 K_5}\left(.393 + 20690 K_{36}^2\right)Ⓕ\left\{.512\left[\left[\frac{Ⓕ K_{19}}{550 K_5 \left(HP_{INST.}\right)} - 1.474\right]\right]^2 + .335\right\}\right]$$

$$R_{INBOUND} = \int_{W_{BASIC}}^{W_2} \left(\text{Same Expression As } R_{OUTBOUND}\right)$$

$$Ⓐ = 1.073 K_{34} V^2\left[K_{25} + K_{32}\frac{W_{T.O.}}{\omega_s} + K_{26}\frac{W_{T.O.}}{\omega_s}\right]$$

$$Ⓑ = \frac{W_{T.O.}^2}{3.37 K_{27} K_{24} V^2\left[.862\sqrt{\frac{K_6 W_{T.O.}}{\omega}} + K_{10} + K_{11}\right]^2}$$

$$Ⓒ = \left(\frac{W}{W_{T.O.}}\right)^2 \cdot Ⓑ$$

$$Ⓓ = \left[W_1 + \left(\frac{K_{17} - K_{29}}{2}\right)\right]$$

$$Ⓔ = \left(\frac{Ⓓ}{W_{T.O.}}\right)\omega$$

$$Ⓕ = \left\{\frac{Ⓓ}{K_3 + K_4 Ⓔ^{.23}}\sqrt{\frac{Ⓔ}{2 K_{36}}}\right\}$$

TABLE II

SUMMARY OF SYMBOLS FOR WEIGHT AND PERFORMANCE EQUATIONS TILT WING

IBM SYMBOL	AERO OR WEIGHT QUANTITY	REMARKS OR DEFINITION
K_1	$(SHP_{S/L-MIL}/SHP_{HOV\,ALT})_{STATIC}$	Reflects Power Rating @ Hovering Altitude
K_2	ρ_{HOV}	Air Density @ Initial Hovering Altitude
K_3	$\eta_a = K_3 + K_4 \omega^n$	Hovering Rotor Efficiency, Where K_3, K_4 & n Depend on Rotor Operating Conditions
K_4		
K_5	η_L	XMSN Efficiency Incl. Duct & Accessory Losses
K_6	i	No. of Propellers
K_7	V_t	Propeller Tip Speed
K_8	$1.06\,K_w$	Wing Wt. Factor for Flaps, Tilt Mechanism, etc.
K_9	$.6(LF)(TF)/f$	Wing Wt. Factor, LF = Load Factor, TF = Taper Factor, f = Allowable Stress
K_{10}	———	Fuselage Width
K_{11}	———	Total Fuselage to Inboard Prop Clearance
K_{12}	———	% GW for Tail, Gear, Fixed Equipment and Emergency Flotation Equipment
K_{13}	———	Fuselage Wetted Area Constant, $S_F = K_{13} + K_{33}\, C_{W_{avg}}$
K_{14}	———	Power Package Weight per Horsepower
K_{15}	———	Constant Fixed Equipment
K_{16}	W_{FUL}	Fixed Useful Load Weight
K_{17}	———	Payload Carried on Inbound Radius Leg
K_{18}	$SFC_{SL-MIL-STATIC}$	Turboprop Engine
K_{19}	$(SHP_{SL}/SHP_{HOV\,ALT})_{MIL\,STATIC}$	Reflects Hovering Altitude
K_{20}	t_{MIN}	Hovering Time in Minutes
K_{21}	———	Increase in Manufacturer's SFC Value
K_{22}	———	Engine Out Cruise Factor = n eng cruise/ n eng-installed
K_{23}	η_P	Propeller Efficiency, Function of Speed
K_{24}	ρ_{CR}	Air Density @ Cruise Altitude
K_{25}	f	Fuselage Flat Plate Drag Area
K_{26}	$C_{D_{0}\,C_{L_W}=0}$	Wing Profile Drag Coefficient
K_{27}	e	Airplane Efficiency Factor
K_{28}	$SHP_{SL-MIL\,STATIC}/SHP_{ALT-NRP\,@V_{CRUISE}}$	Reflects Cruise Altitude
K_{29}	———	Payload Carried on Outbound Radius Leg
K_{30}	$t_{W/U,\,CLIMB}$	Warm Up and Climb Time in Minutes
K_{31}	$(SHP_{SL}/SHP_{CR\,ALT})_{MIL\,STATIC}$	Reflects Cruise Altitude
K_{32}	———	Constant for Tail Group Flat Plate $= \frac{S_T}{S_W} \times C_{D_t}$
K_{33}	———	Constant for Fuselage Wetted Area
K_{34}	———	Reserve and Tankage Factor
K_{35}	———	Variable Portion of Fixed Useful Load
K_{36}	ρ_{HOV}	Air Density @ Hovering Altitude - Mission Midpoint

Disc loading was considered as a prime input variable with a range of 30 to 60 pounds per square foot. Previous VTOL studies have indicated the optimum wing loading for this configuration to be of the order of 80 to 100 pounds per square foot. For the purpose of this analysis a constant value of 80 lbs/ft^2 was considered. Cruise speed, as mentioned previously, was held constant at 300 mph.

C. Vertodyne Analysis

This configuration employs ducted fans submerged in the wing for hovering with thrust in forward flight derived from turbojet engines located on the wing outboard of the fans. In hovering the ducted fans are driven by modifying the turbojet engines to drive a free turbine from which shaft power can be drawn.

Both the wing span and area have been expressed as a function of the diameter of the ducted fan so that they are introduced into the equations as a function of the basic variables of fan disc loading and gross weight.

Power required in hovering has been based on the ducted fan power loading curve (Reference 1). Thrust required in forward flight has been calculated on a parasite drag area composed of a constant value for fuselage with wing and tail areas of course varying according to the size of the wing. The change in parasite drag with wing lift coefficient has been introduced through an airplane efficiency factor in the wing induced drag term.

The drive system and ducted fan weights have been based on hovering power (HP_{inst}) only, with the number of installed power plants determined by the equivalent shaft horsepower attainable from a modified J-79 turbojet. Power plant characteristics of thrust and fuel flow are based on the data of Reference 1 and is summarized in Section E of this report.

Disc loading was considered as a prime input variable with a range of 160 to 300 pounds per square foot. Two submerged ducted fans, one in each semi-span, were considered throughout this study. Cruise speed, as mentioned previously, was held constant at 450 mph.

D. Weight Trends

In general, the weight trends as set forth in Reference 1 have been followed in this more detailed study of the Tilt Wing Propeller and Vertodyne VTOL concepts. Table V lists the weight expressions used in this investigation. Changes from

TABLE 3 - DETAIL FLOW DIAGRAM

INPUT VARIABLES				
	$W_{T.O}$			
	ω			
	V			

$$HP_{INST._1} = \frac{.0543\,K_1\,W_{T.O.}}{K_5\,K_2^{.5}\left[K_3 - K_4\,\omega^{.25}\right]}$$

$$HP_{INST._2} = \frac{1.7\,K_{31}}{\left(\frac{V-300}{1000}\right)^2 + .91}\left[Ⓐ + Ⓑ\right]$$

USE LARGER VALUE

$$n_{INST.} = \frac{HP_{INST.}}{13600} \quad \text{where, } n_{INST.} \geq 2 \leq 8 \text{ (Use next larger } \underline{\underline{\text{EVEN}}} \text{ integer!)}$$

$$W_{BASIC} = K_2\left\{W_{T.O.}^{.25}\,Ⓕ^{.75} + \frac{K_9\,W_{T.O.}\,Ⓖ^3}{Ⓕ}\right\} + 496\left\{W_{T.O.}^2 \cdot 10^{-10} \cdot \left[K_{13} + (K_{32})\frac{Ⓕ}{Ⓖ}\right]\right\}^{.24} + K_{12}W_{T.O.} + K_{14}(HP_{INST.}) + 72.2K_6\left[\frac{(HP_{INST._1})\,W_{T.O.}^2}{K_7^3\,K_6^3\,\omega^{1.5}\,K_2^{.5}\,K_1}\right]^{.27} + 8.4\left[\frac{(HP_{INST._1})^2}{K_6^2\,K_7\sqrt{\frac{K_6\,\omega}{W_{T.O.}}}}\right]^{.333}$$

$$.0815\left[\frac{HP_{INST._1}}{K_1\,K_6}\right]^{.5}\left[(2)\cdot\sqrt{\frac{1.273\,W_{T.O.}}{K_6\,\omega}} + (K_{10}+K_{11})\right] + .0841\sqrt{\frac{HP_{INST._1}\cdot W_{T.O.}}{K_6\,\omega}} + (K_{15}+K_{16}+K_{17}) + (n_{INST.})\left[K_{35} + .93\left(\frac{HP_{INST.}}{n_{INST.}}\right)^{.67}\right]$$

ASSUME W_1 & EVALUATE $R_{OUTBOUND}$

$$R_{OUTBOUND} = V\int_{W_1}^{W_{T.O.} - \frac{.0167\,HP_{INST.}\,K_{19}\,K_{30}\,K_{21}\,K_{34}}{1.36}} \frac{dW}{\left[Ⓐ+Ⓒ\right]K_{11}K_{23}K_{21}\left\{.7466\left[\frac{\left[Ⓐ+Ⓒ\right]K_{31}\,(1.36)}{HP_{INST.}\,(K_{36})} - .625 - .0004V\right]^2 + .895 + .0305\left(\frac{V}{100}\right)\right\}}$$

$$\begin{cases} n_{CR.} = 1.25\,(n_{INST.})\left(\frac{\left[Ⓐ+Ⓒ\right]}{HP_{INST.}}\right)K_{31}\,(1.36) & \text{where, } n_{CR.} \geq 2 = 8 \\ \therefore K_{36} = \frac{n_{CR.}}{n_{INST.}} & \end{cases}$$

(Use next larger <u>EVEN</u> integer!)

$$W_2 = W_1 + K_{17} - K_{24} - \left[\frac{Ⓒ\,K_{23}\,K_{34}\,K_{21}\left(\frac{K_{30}}{60}\right)K_{19}}{1.36}\left\{.7466\left[\frac{Ⓒ\,K_{37}}{HP_{INST.}} - .625\right]^2 + .895\right\}\right]$$

$$R_{INBOUND} = V\int_{W_{BASIC}}^{W_2} \text{(SAME EXPRESSION AS } R_{OUTBOUND}\text{)}$$

$$Ⓐ = 1.073\,K_{24}\,V^2\left\{K_{25} + \left[K_{22} + K_{26}\right]\left[Ⓕ\right]\right\}$$

$$Ⓑ = \frac{W_{T.O.}^2}{3.37\,K_{27}\,K_{24}\,V^2\left[Ⓖ\right]^2}$$

$$Ⓒ = \left(\frac{W}{W_{T.O.}}\right)^2 \cdot Ⓑ$$

$$Ⓓ = \left[W_1 + \left(\frac{K_{17} - K_{24}}{2}\right)\right]$$

$$Ⓔ = \frac{.0543\,Ⓓ}{K_5\,K_{38}^{.5}\left[K_3 - K_4\,\omega^{.25}\left(\frac{Ⓓ}{W_{T.O.}}\right)^{.25}\right]}$$

$$Ⓕ = \left[\frac{1.273\,W_{T.O.}\,K_{23}}{K_6\,\omega}\left(2 + K_{19} + K_{18}\cdot K_{32}\right) + K_{23}\sqrt{\frac{1.273\,W_{T.O.}}{K_6\,\omega}}\left(K_{10} + K_{11}\right)\right]$$

$$Ⓖ = \left[2\left(1 + K_{19}\right)\sqrt{\frac{1.273\,W_{T.O.}}{K_6\,\omega}} + \left(K_{10} + K_{11}\right)\right]$$

TABLE IV

SUMMARY OF SYMBOLS FOR WEIGHT AND PERFORMANCE EQUATIONS
VERTODYNE

IBM SYMBOL	AERO OR WEIGHT QUANTITY	REMARKS OR DEFINITION
K1	$(SHP_{SL-MIL}/SHP_{HIGH\ ALT})_{STATIC}$	Reflects Power Rating @ Hovering Altitude
K2	$\rho_{HOV.}$	Air Density @ Hovering Altitude
K3 K4	$\left.\right\} \Lambda_a = K_3 - K_4\, \omega^{.35}$	Ducted Fan Power Loading @ Sea Level
K5	η_L	XMSN Efficiency Incl. Duct & Accessory Losses
K6	i	No. of Ducted Fans
K7	V_t	Ducted Fan Tip Speed
K8	$1.06\ K_w$	Wing Wt. Factor for Flaps, Tilt Mechanism, etc.
K9	$.6(LF)(TF)/f$	Wing Weight Factor LF = Load Factor, TF = Taper Factor, f = Allowable Stress
K10	—	Fuselage Width
K11	—	Total Fuselage to Ducted Fan Clearance
K12	—	% GW for Tail, Gear, Fixed Equipment and Emergency Flotation Equipment
K13	—	Fuselage Wetted Area Constant
K14	K_P	Power Package Weight per Horsepower
K15	—	Constant Fixed Equipment
K16	W_{FUL}	Fixed Useful Load Weight
K17	—	Payload Carried on Inbound Radius Leg
K18	$SFC_{SL-MIL-STATIC}$	Turbojet Engine
K19	—	Factor Applied to Duct Diameter for Outboard Span
K20	t_{MIN}	Hovering Time in Minutes
K21	—	Increase in Manufacturer's SFC Value
K22	—	Wing Taper Ratio Outboard of Ducted Fans
K23	—	Factor Applied to Duct Diameter for Wing Root Chord
K24	$\rho_{CR.}$	Air Density @ Cruise Altitude
K25	f	Fuselage Flat Plate Drag Area
K26	$C_{D_0 C_{L_w}=0}$	Wing Profile Drag Coefficient
K27	e	Airplane Efficiency Factor
K28	$(SFC_{CR-ALT}/SFC_{SL})_{\substack{MIL\\STATIC}}$	Turbojet Engine
K29	—	Payload Carried on Outbound Radius Leg
K30	$t_{WU-CLIMB}$	Warm Up and Climb Time in Minutes
K31	$(T_{0SL}/T_{0CR-ALT})_{\substack{MIL\\STATIC}}$	Turbojet - Reflects Cruise Altitude
K32	—	Constant for Tail Group Flat Plate = $\frac{S_T}{S_W} \times C_{D_{0T}}$
K33	—	Constant for Fuselage Wetted Area
K34	—	Reserve & Tankage Factor
K35	—	Variable Portion of Fixed Useful Load
K36	n_{CR}/n_{INST}	Engine Out Cruise Factor
K37	$(T_{0SL}/T_{0HOV.\ ALT})_{\substack{MIL\\STATIC}}$	Turbojet - Reflects Hovering Altitude
K38	ρ_{HOV}	Air Density @ Hovering Altitude - Mission Midpoint

the previously established trends are noted and explained in the following paragraphs.

The basic wing weight trend equation remains unchanged, but the factor to adjust for special features has been reduced for the Tilt Wing Propeller from 1.2 to 1.05 as a result of preliminary design analysis of a wing for this concept (Reference 2).

The tail weight for both versions has been increased by .005W to give a more conservative weight for pitch and yaw control devices included in the tail weight. The landing gear weight has also been increased by .005W to provide a gear that has STOL possibilities.

Propulsion group weight has been modified to include the lubrication and fuel systems, which were previously considered as portions of useful load. The engine reduction gear weight has been changed to vary as the 2/3 power of horsepower instead of the previous assumption of a constant pounds per horsepower. This new expression represents a gearbox having an output speed of 6000 RPM for the tilt wing and 8000 RPM for the Vertodyne instead of conventional propeller speeds.

For the tilt wing concept the engines are located in the fuselage instead of in the wing as assumed in Reference 1. Therefore the drive system weight expressions have been adjusted to reflect this change. In addition, the rotor or propeller extension shaft trend has been modified to give more realistic results. The vertodyne propeller transmission weight is based on a turboprop planetary reduction gearbox trend presented in Reference 3.

The above minor changes in the weight expressions have a negligible effect on the final gross weights or the comparative position, weight-wise, of the Tilt Wing Propeller and Vertodyne VTOL concepts. It is believed that these changes give a more accurate distribution of weight empty to the various component groups.

E. Power Plant Data

A compilation of engine characteristics has been made in Reference 1. Specific fuel consumption and specific weight of representative shaft turbine and turbojet engines were plotted against the date of availability to allow the construction of curves representing the trend of technological improvement from which predicted 1962 values were obtained. Further, from existing engine data, average ratios of part load specific fuel

TABLE V

SUMMARY VTOL WEIGHT TRENDS - DETAIL STUDY

ITEM	TILTING WING ENGINES ON FUSELAGE	VERTODYNE ENGINES ON WING	CORRELATION FACTOR K
Rotor Group/Rotor	$748\,K^{0.31} \times N_P$	$1250\,K^{0.27} \times N_P$	$\frac{HP \times D^3 \times \sigma^{-.5}}{\Omega \times 10^4}$
Wing Group	$1.05\,K$	$1.3\,K$	$1.06\left[41.57\,C_1\,\omega_W^{.25}A + \frac{0.6\,LF \times TF \times b^3 \times \omega_W}{f}\right]$
Tail Group	$.035\,W$	$.035\,W$	
Body Group	$496\,K^{0.34}$	$496\,K^{0.34}$	$W^2 S_F \times 10^{-10}$
Alighting Gear	$.05\,W$	$.05\,W$	
Propulsion Group Engine, etc.*	0.421 LBS. $/HP_{TOTAL}$	0.533 LBS $/HP_{TOTAL}$	
Reduct. Gear.	$0.96\,\overline{HP}^{.67} \times N_E$	$0.93\,\overline{HP}^{.67} \times N_E$	
P.P. Controls	$20 \times N_E$	$25 \times N_E$	
Fuel Tank	.13 LBS. /GAL. FUEL	.13 LBS /GAL. FUEL	
Drive System Eng. Mixing Box	$130\,K^{.5} \times N_E$	————	$\frac{HP/ENG.}{6000}$
Prop. XMSN's Inboard	$175\,K^{.5} \times N_X$	————	$\frac{HP/PROP}{\Omega/PROP}$
Outboard	$130\,K^{.5} \times N_X$	$21.5\left(\frac{\overline{HP}^2}{\Omega_{PROP}}\right)^{.333}$	$\frac{HP/PROP}{\Omega/PROP}$
Sync. Shaft	$6.3\,K^{.5} \times L$	$6.3\,K^{.5} \times L$	$\frac{HP}{\Omega}$ XMITTED
Eng. Shaft	$6.3\,K^{.5} \times L$	$6.3\,K^{.5} \times L$	$\frac{HP/ENG.}{6000}$ TILT. WING $\frac{HP/ENG.}{8000}$ VERT.
Rotor Extension Shaft	$6.7\,K^{.5} \times L$	————	$\frac{HP}{\Omega}$ XMITTED
Fixed Equipment**	$2380 + .026\,W$	$2380 + .025\,W$	
Useful Load***	$8850 + 110\,N_E + 6.5$ LBS/GAL FUEL	$8800 + 110\,N_E + 6.5$ LBS/GAL. FUEL	

*Eng. Sect., Eng. Access., Starting Sys., Cooling Sys., Lube Sys., & Fuel Sys.
**These values apply only for the Gross Weight Range and Mission of this study.
***Includes 8,000 lbs. payload.

consumption at various flight speeds to static military rating for a typical shaft turbine and turbojet were obtained. These studies were used as a basis of the power plant data used in this analysis.

For a "1962" turboprop engine, a specific weight of .24 pounds per military static horsepower was assumed for the bare engine (without reduction gearing). The military rated specific fuel consumption at sea level was .50 lbs/SHP/hr. Part load fuel consumption characteristics are indicated in Figure 5.

For the Vertodyne concept, a "1962" turbojet engine without afterburners was assumed to have a specific weight of .21 pounds per military static thrust. This value was increased by 20% to reflect the modifications necessary to provide shaft horsepower in hovering flight. A value of .80 lbs/lbs/hr was assumed for military rated specific fuel consumption. Part load operation is depicted in Figure 6. It should be noted that the rated thrust and/or horsepower was decreased 15% to account for losses for the necessary modifications of the basic engine.

III. RESULTS AND CONCLUSIONS

The effect of hovering ceiling, cruise altitude and hovering duration on the minimum gross weight for the Tilt Wing Propeller aircraft is summarized in Figures 1 and 2 and for the Vertodyne concept in Figures 3 and 4. Each point along these curves represent an optimum combination of parameters and are distinct aircraft designed to meet the particular requirements.

Although the combined effect of the various performance variables must be considered in an overall evaluation, it is interesting to determine the effect of a particular criterion on the optimum size while keeping the remaining variable constant. These effects can only be determined approximately since the variation of gross weight is not linear.

However, for the Tilt Wing Propeller, it can be seen from Figure 1 that changing the design hovering ceiling from sea level to 10,000 feet increases the gross weight some 23%, while changing cruise altitude from sea level to 10,000 feet decreases the gross weight by approximately 11%. Increasing the hovering duration from one to ten minutes increases the gross weight by 6%.

From Figure 3 the results of the Vertodyne analysis indicates similar trends but shows clearly the strong inter-relation of the various performance criterion. Increasing the design hovering ceiling from sea level to 10,000 feet increases the take-off gross weight about 35% for a cruise altitude of sea level, 30% for a cruise altitude of 10,000 feet and only 8% for cruising at 25,000 feet. This effect is especially noticeable for the Vertodyne since the ducted fans are submerged in the wing and the wing area (or wing loading) varies with the disc loading. Consequently, wing loading is relatively low and cruise altitude obviously plays a stronger role in determining the optimum aircraft size. Variation of gross weight with cruise altitude is shown in Figure 4. It is noted, once again, that as the hovering requirement becomes more stringent, cruise altitude becomes increasingly important. Hovering duration, at least for the times investigated, is not as important but does indicate a similar trend.

Due to the limited time and scope of the study program, the analysis presented herein is far from complete and only indicative of the trends that may be expected. The performance criteria that were varied are believed to be the most important. However, a more thorough investigation should be made to obtain a complete evaluation of the effect of basic design and <u>operational</u> requirements for an overall comparison of VTOL aircraft.

FIGURE 1

TILT WING
EFFECT OF HOVERING CEILING ON TAKE-OFF GROSS WEIGHT

Cruise Speed = 300 MPH
Radius of Action = 425 Statute Miles
Outbound Payload = 8000#
Inbound Payload = 4000#

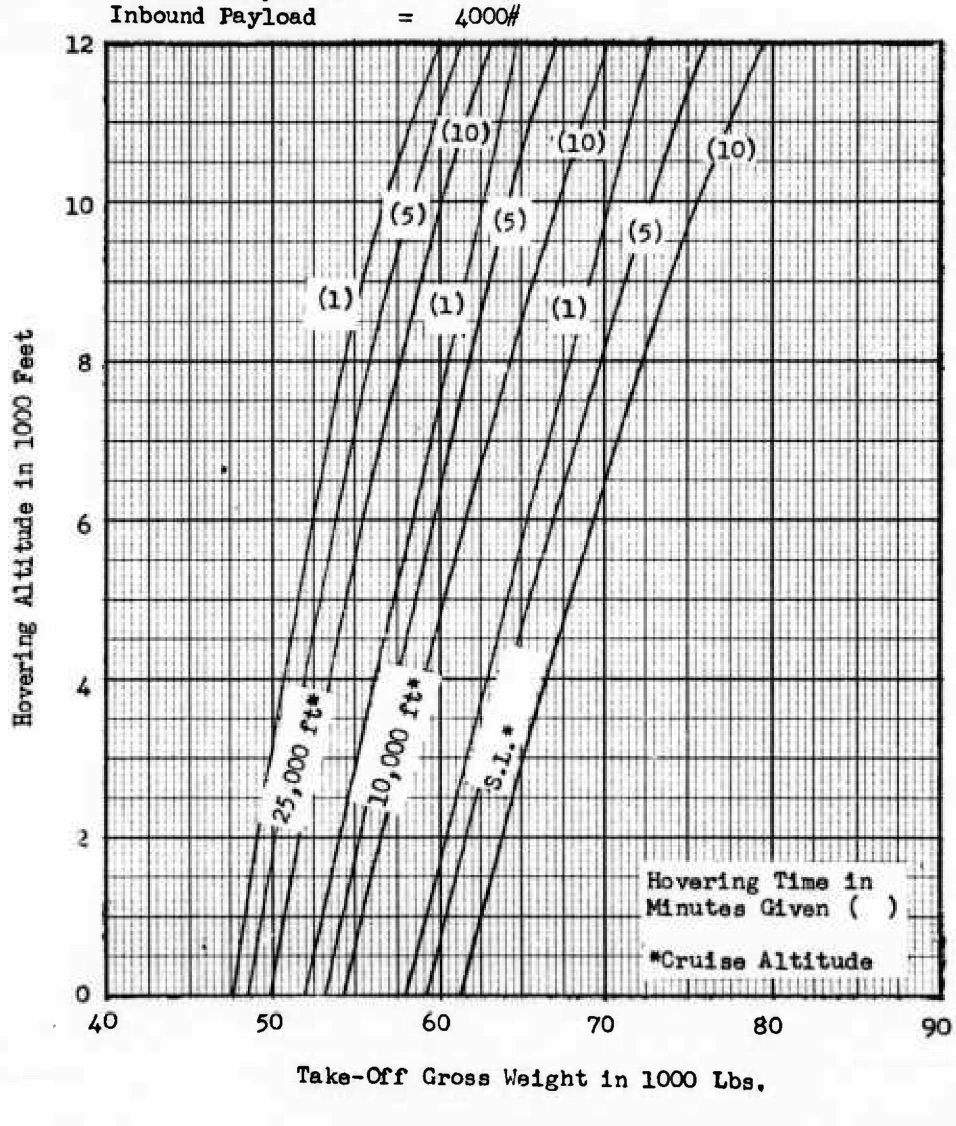

FIGURE 2

TILT WING
EFFECT OF CRUISE ALTITUDE ON TAKE-OFF GROSS WEIGHT

Cruise Speed	=	300 MPH
Radius of Action	=	425 Statute Miles
Outbound Payload	=	8000#
Inbound Payload	=	4000#

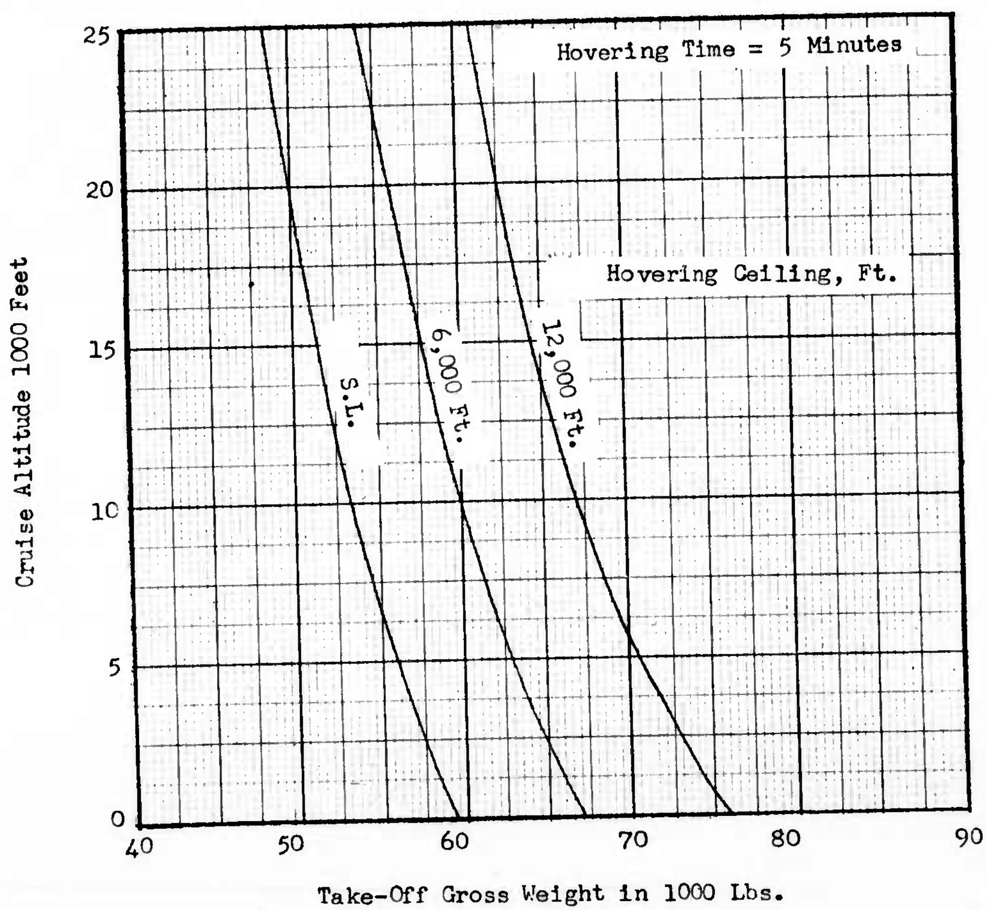

FIGURE 3

VERTODYNE
EFFECT OF HOVERING CEILING ON TAKE-OFF GROSS WEIGHT

Cruise Speed = 450 MPH
Radius of Action = 425 Statute Miles
Outbound Payload = 8000#
Inbound Payload = 4000#

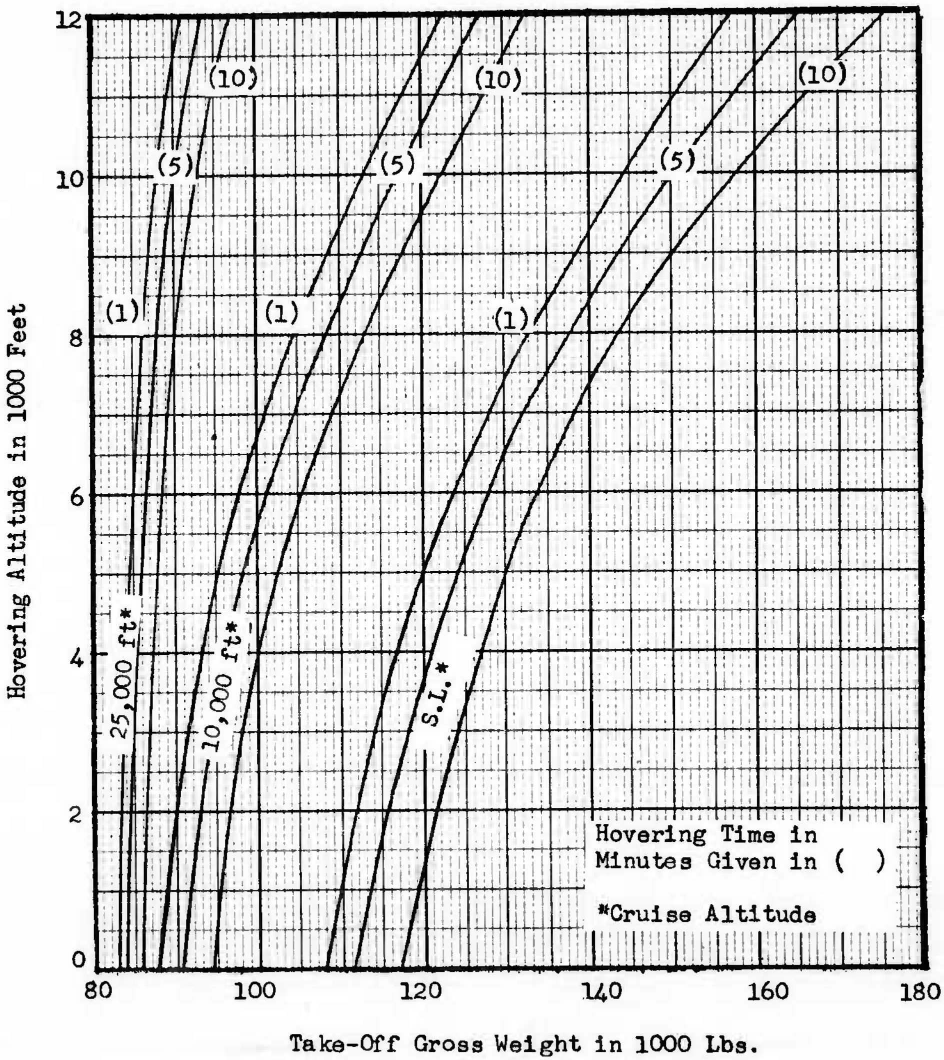

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FIGURE 4

VERTODYNE
EFFECT OF CRUISE ALTITUDE ON TAKE-OFF GROSS WEIGHT

Cruise Speed	=	450 MPH
Radius of Action	=	425 Statute Miles
Outbound Payload	=	8000#
Inbound Payload	=	4000#

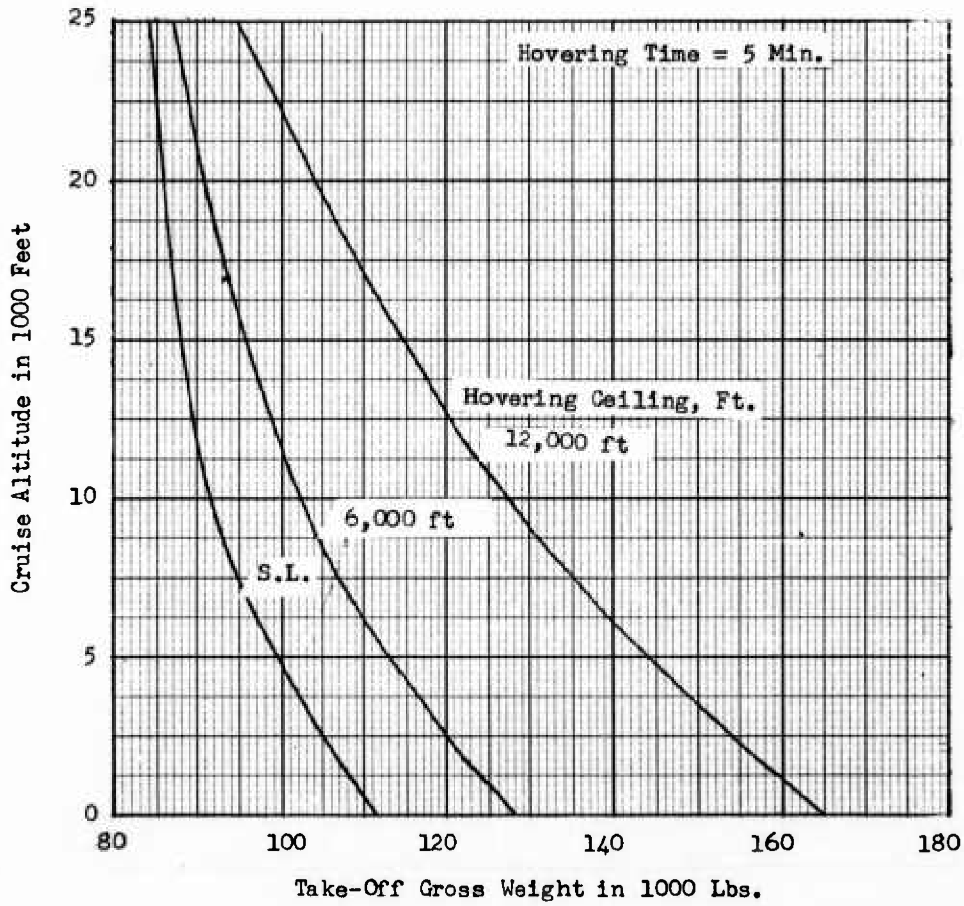


FIGURE 5

TURBOPROP FUEL CONSUMPTION TREND

$\frac{SFC}{SFC_{MIL}}$ vs $\frac{SHP}{SHP_{MIL}}$

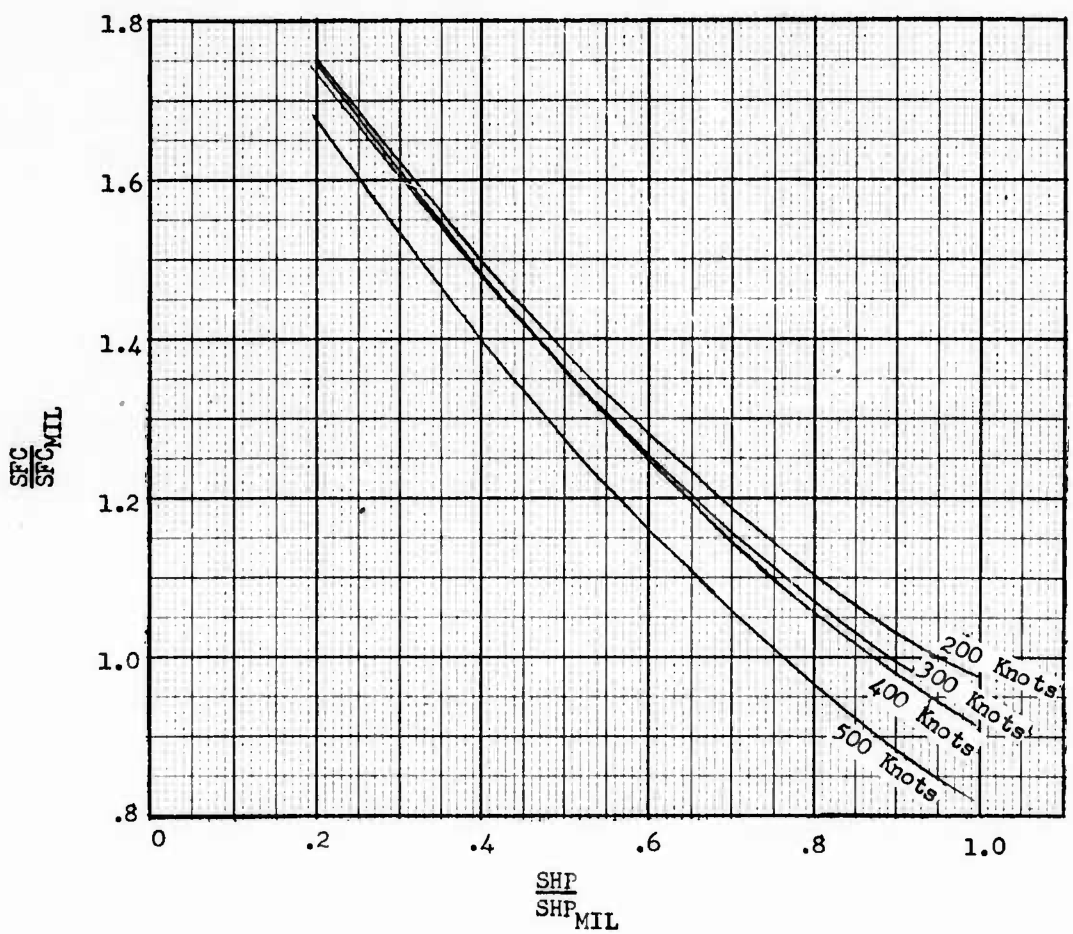
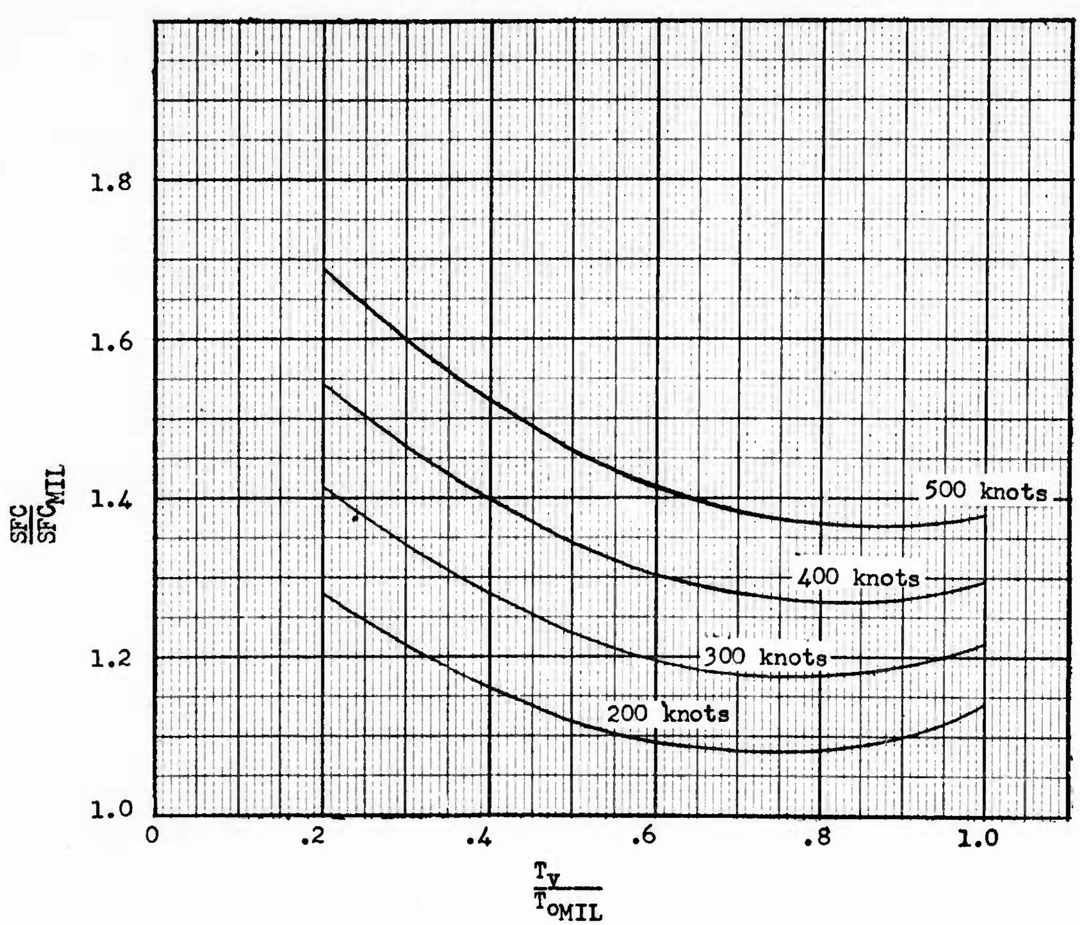


FIGURE 6

TURBOJET FUEL CONSUMPTION TREND



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